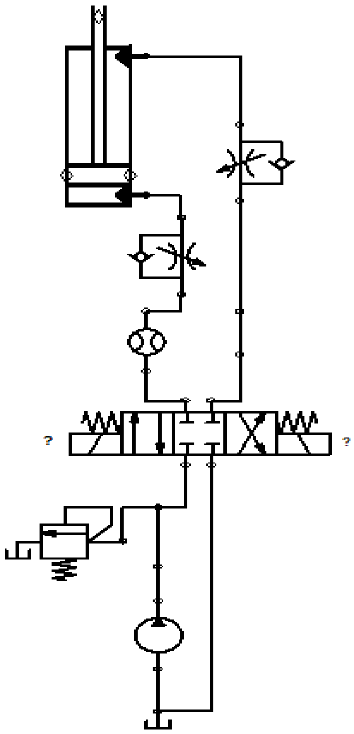
Chapter (3) : Hydraulic circuit design

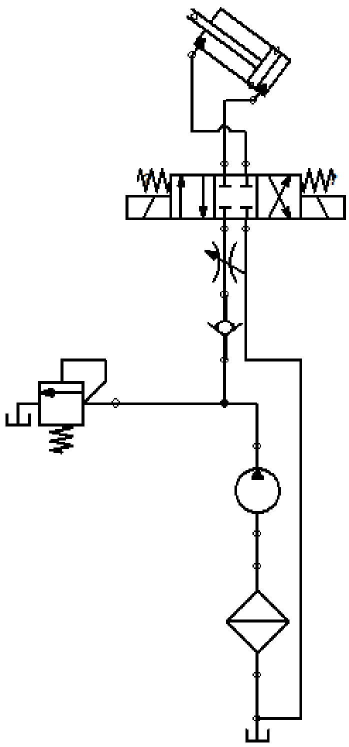
In order to improve design performance, shorten development cycles, reduce production cost, designed the forklift hydraulic system. By the analysis of the forklift tilting and lifting process, the forklift hydraulic system schematic is made. Based on the schematic, designed and calculated the size and operating parameter of hydraulic cylinder, the pump operating parameter, hydraulic valve operational parameter, hydraulic oil tank effective volume, pipe size, selected the appropriate hydraulic components, and checked the system pressure loss and temperature rise the results show that the hydraulic system meets the requirements.

Hydraulic Circuits used in the project

Circuit 1 (Lifting) : this circuit shows a solenoid spring centered 4/3 directional control valve mounted to a double acting cylinder (Front Flange Mounting) with flow control valve (non pressure compensated valve), This circuit is used to lift the load, taking into account the maximum load that the forklift can lift it.

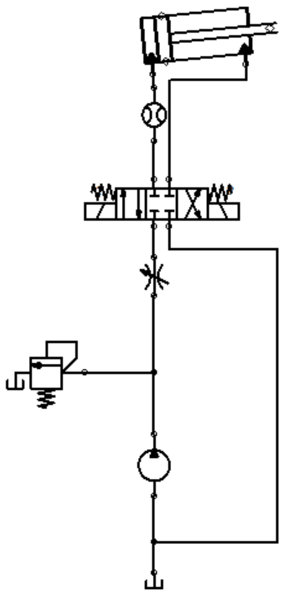


Circuit 2 (Steering) : this circuit shows a solenoid spring centered 4/3 directional control valve mounted to a double acting cylinder (clevis mounting) with flow control valve (needle valve) and with check valve.



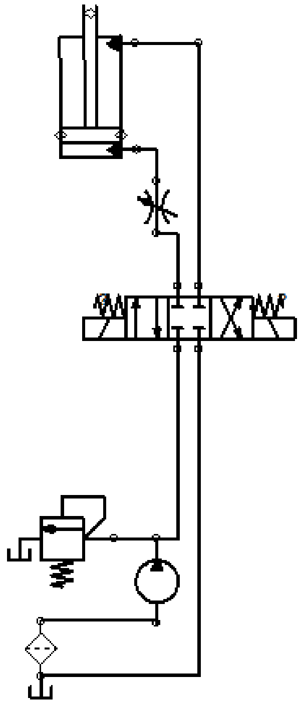
This circuit is used for the steering the forklift.

Circuit 3 (Tilting) : Shown figure shows a solenoid spring centered 4/3 directional control valve mounted to a double acting cylinder(clevis mounting) with flow control valve (needle valve) and with check valve.



This system allows for incline the Mast System to and (picking aid) and to back (centering aid).

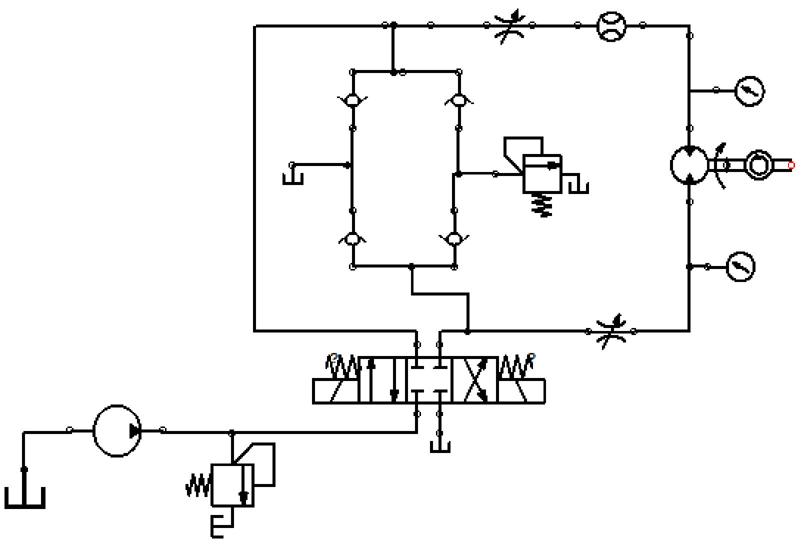
Circuit 4 (Carriage) : The shown circuits in figure shows the Push and pull The Mast Package. This circuit shows a spring solenoid centered 4/3 directional control valve mounted to a double acting cylinder (clevis Mounting) with flow control valve (non pressure compensated valve). Very Important Mechanism used to adjust the C.G in the Safety triangle.



It allows a little compactness in fork design

Circuit 5 (Hydro Transmission) :

Hydro Transmission system, This system shows a solenoid actuated spring return (closed center) 4/3 directional control valve, Brake system (different arrange of four check valves) control the hydraulic motor with flow control valve (non compensated valve).



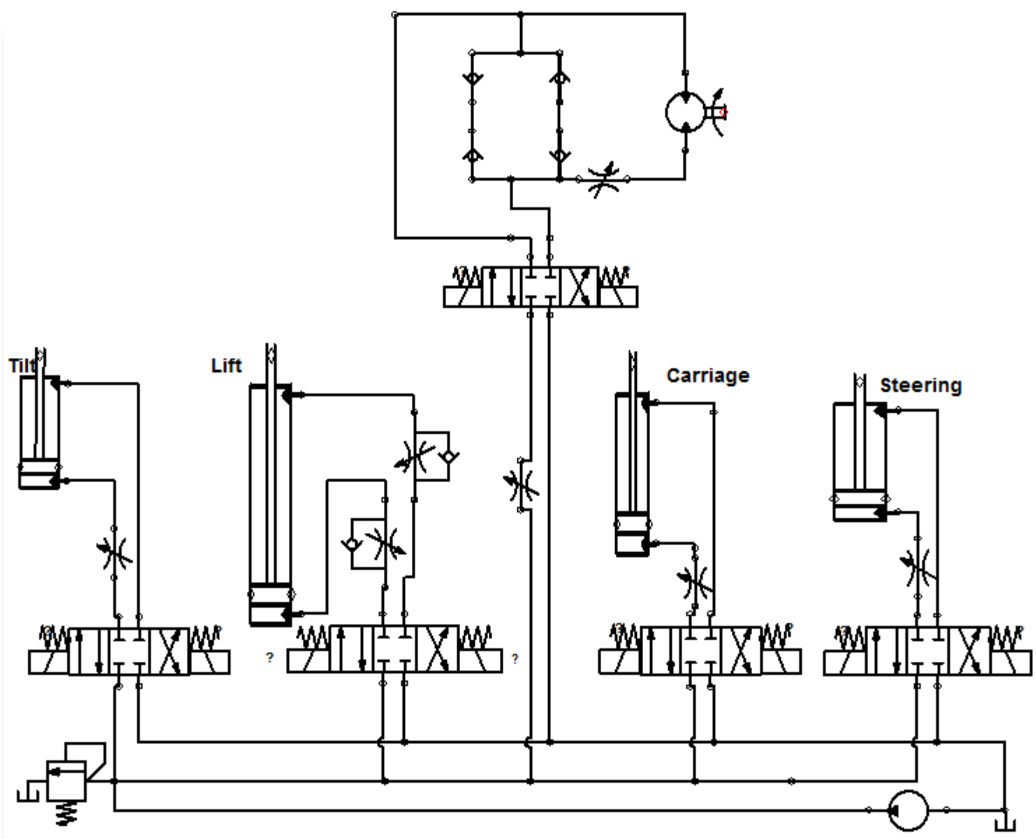
The Development of hydraulic schematic diagram

1- Determine the supply mode : Taking into account the larger load, Slower speed when lift hydraulic cylinder work, Caring with saving energy and reducing heat. The system source pumping oil should be a fixed displacement pump. Choosing the one way gear pump to operate the project.

2- The order and it's speed of working mode choice : the system depends on D.C.Vs -(spring return, closed neutral centers)- with solenoids, attached to them some throttling valves to control the flow rate in the two directions of actuating.

3- Action goals achieved by different types of actuators (Cylinders and Motors). The cylinders selected of the type of double acting actuating cylinders to supply motion in two directions with different speeds, by the way there is a powerful hydraulic motor that drives wheels.

Next there will be the assembled hydraulic circuit of the smart design, all components are connected to the pump, and all return lines are leads to the tank.



Motor Load Calculations

Requirements:

Truck weight = 2500 N (load) + 2500 N (chassis and component) = 5000 N.

Weight per wheel = 2000 N, Wheel radius = 0.185 m, Max. speed = 0.5 m/s, Acceleration time = 1 sec. , Inclination angle = 5 degrees, Floor type = rough concrete (C_r = 0.02).

Using: TTE = $F_{Rolling} + F_{Slope} + F_{Acc}$

$F_{Rolling}$ = WEIGHT × C_r = 5000 × 0.02 = 100 N

F_{Slope} = WEIGHT × Sin (α) = 5000 × Sin(5) = 436 N (Not taken into account because of flat floor)

F_{Acc} = WEIGHT × MAX.VELOCITY / ACC.TIME × g = $\frac{5000 \times 0.5}{1 \times 10}$ = 250 N

So TTE = (100 + 250) = 350 N

Then Motor required torque = TTE × wheel radius × bearing friction factor

= 350 × 0.185 × 1.1 = 71.25 N.m

Using a differential with a reduction ratio of (3.75) to reduce torque and increase speed and vise versa.

By the way: the required torque by the hydraulic motor = 19 N.m

Motor Volume = $\frac{Torque \times 2\pi}{Pressure}$ (Volume depends on circuit pressure)

Used Pressure in Motor circuit (Bar)	Required Motor Volume (c.c)
10	119
15	79.5
20	59.7
30	39.8

It's required to move the truck by a Velocity = 2 Km/h = 0.5 m/s

Remember that: Wheel Raduis = 18.5 Cm = 0.185 m

So $\omega_{\text{on wheels}}$ = v / r = 0.5 / 0.185 = 2.7 rad/s , Speed = 26 rpm

<u>Using (n=3.75)</u>

So ω on motor = 10.25 rad/s , Speed = 98 rpm

Where Motor Mechanical power = Torque × ω = 19 × 10.25 = 195 watt.

And it's hydraulic Power = 216.66 watt. (Taking mechanical Efficiency = 90%)

It's clear that the calculations leaded us to choose a pressure = 15 Bar , 100 cc/r Motor, and there is a close match between real standard motors and calculations.

Flow rate Calculations

Also Hydraulic power = P × Q

So Motor flow rate (Q) = Hydraulic power / Pressure

= 216.66 / 1500000 = 0.000144 m^3/s = 8.6 LPM

So Pump Power = 216.66/0.9 = 240.7 watt , (with Efficiency = 90% for hoses and connections)

So prime mover Power = 240.7/0.9 = 268 watt

= 0.268 kw

= 0.357 HP

Lift Cylinder Calculations

&

Pump and Electrical Motor Selection

For a max. load on forks = 2500 N , Using 15 Bar (Assumed Pressure).

$A_{Piston} = F_{Load} / P = 2500 / 1500000 = 0.00166\ m^2$

Then $D_{Piston} = 0.045\ m = 1.97\ in$, $D_{Rod} = 0.0254\ m = 1\ in$

HYDRAULIC CYLINDER SPEEDS (inches per minute)													
PISTON DIA	ROD DIA	1 GPM	3 GPM	5 GPM	8 GPM	12 GPM	15 GPM	20 GPM	25 GPM	30 GPM	40 GPM	50 GPM	75 GPM
1½	none	130	392	654	1034	–	–	–	–	–	–	–	–
	⅝	158	476	792	1265	–	–	–	–	–	–	–	–
	1	235	706	1176	1880	–	–	–	–	–	–	–	–
2	none	73	221	368	588	883	1120	–	–	–	–	–	–
	1	97	294	490	782	1175	1465	–	–	–	–	–	–
	1⅜	139	418	697	1115	1673	2090	–	–	–	–	–	–
2½	none	47	131	235	376	565	675	940	1175	–	–	–	–
	1	56	168	280	448	672	840	1120	1400	–	–	–	–
	1⅜	67	203	339	542	813	1015	1355	1695	–	–	–	–
	1¾	92	277	463	740	1110	1385	1850	2310	–	–	–	–
3¼	none	28	83	139	223	334	417	557	696	836	1115	–	–
	1⅜	34	102	170	271	407	510	680	850	1020	1360	–	–
	1¾	39	118	196	313	472	588	784	980	1176	1568	–	–
	2	44	134	224	358	537	672	896	1120	1344	1792	–	–
4	none	18	55	92	147	220	276	368	460	552	736	920	–
	1¾	22	68	113	182	273	339	452	565	678	904	1130	–
	2	24	73	122	196	294	366	488	610	732	976	1220	–
	2½	30	90	150	241	362	450	600	750	900	1200	1500	–
5	none	12	35	58	94	141	174	232	290	348	464	580	870
	2	14	42	70	112	168	210	280	350	420	560	700	1050
	2½	16	47	78	125	188	235	315	390	470	630	780	1170
	3	18	55	92	147	220	275	365	460	550	730	920	1380
	3½	22	66	111	178	266	333	444	555	665	888	1110	1665
6	none	8	24	41	65	98	123	162	202	245	320	405	606
	2½	10	30	50	79	118	150	200	250	300	400	495	750
	3	11	33	54	87	130	165	206	270	325	435	545	810
	3½	12	37	62	99	148	185	245	310	370	495	615	830
	4	15	44	73	117	176	220	295	365	440	585	735	1095
7	none	6	18	30	48	72	90	120	150	180	240	300	450
	3	7	22	37	59	88	110	145	185	220	295	365	555
	3½	8	24	40	64	96	120	160	200	240	320	400	600
	4	9	27	45	71	107	135	180	225	270	360	445	675
	4½	10	31	51	82	122	153	205	255	305	410	515	765
	5	12	37	61	98	147	185	245	305	370	490	615	915
8	none	4	14	23	36	55	69	92	115	135	185	230	345
	3½	5½	17	28	45	68	85	115	140	170	230	285	420
	4	6	18	30	49	73	90	122	150	180	240	305	450
	4½	6½	20	33	53	80	100	135	165	200	265	335	495
	5	7½	22	38	60	90	114	150	185	225	300	375	555

Reviewing the standard productions, it was available to use a cylinder with a Piston Diameter (5 Cm) and Rod Diameter (2.5 Cm).

The Stroke (S) = 0.8 m (Design Assumed Value).

Stroke Volume (V) = $A_{Piston} \times$ Stroke $= 0.00166 \times 0.8 = 0.00133\ m^3$

The load will be lifted during 15 seconds (Design Assumed Value).

So The required flow rate (Q) = Stroke Volume / Lift time = 0.00133 / 15 = $0.000088\ m^3/s$ = 5.28 LPM

Hydraulic Power = $P \times Q = 1500000 \times 0.000088$ = 132 watt = 0.176 HP

Taking Hydraulic efficiency through hoses and connections = 80%

So Pump Required power = 165 watt = 0.22 HP

(Taking pump overall Efficiency = 80%)

So Electric Motor Required Electrical Power = 206 watt =0.275 HP

Carriage Cylinder Calculations

For max. load on carriage cylinder = Maximum load ×Friction factor

$$= 3000 \times 0.2 = 600\ N$$

Using 5 Bar (Assumed Pressure).

$A_{Piston} = F_{Load} / P = 600 / 500000 = 0.0012\ m^2$

Then $D_{Piston} = 0.039\ m = 1.57\ in$, $D_{Rod} = 0.02\ m = 5/8\ in$

HYDRAULIC CYLINDER SPEEDS (inches per minute)													
PISTON DIA	ROD DIA	1 GPM	3 GPM	5 GPM	8 GPM	12 GPM	15 GPM	20 GPM	25 GPM	30 GPM	40 GPM	50 GPM	75 GPM
1½	none	130	392	654	1034	–	–	–	–	–	–	–	–
	⅝	158	476	792	1265	–	–	–	–	–	–	–	–
	1	235	706	1176	1880	–	–	–	–	–	–	–	–
2	none	73	221	368	588	883	1120	–	–	–	–	–	–
	1	97	294	490	782	1175	1465	–	–	–	–	–	–
	1⅜	139	418	697	1115	1673	2090	–	–	–	–	–	–
2½	none	47	131	235	376	565	675	940	1175	–	–	–	–
	1	56	168	280	448	672	840	1120	1400	–	–	–	–
	1⅜	67	203	339	542	813	1015	1355	1695	–	–	–	–
	1¾	92	277	463	740	1110	1385	1850	2310	–	–	–	–
3¼	none	28	83	139	223	334	417	557	696	836	1115	–	–
	1⅜	34	102	170	271	407	510	680	850	1020	1360	–	–
	1¾	39	118	196	313	472	588	784	980	1176	1568	–	–
	2	44	134	224	358	537	672	896	1120	1344	1792	–	–
4	none	18	55	92	147	220	276	368	460	552	736	920	–
	1¾	22	68	113	182	273	339	452	565	678	904	1130	–
	2	24	73	122	196	294	366	488	610	732	976	1220	–
	2½	30	90	150	241	362	450	600	750	900	1200	1500	–
5	none	12	35	58	94	141	174	232	290	348	464	580	870
	2	14	42	70	112	168	210	280	350	420	560	700	1050
	2½	16	47	78	125	188	235	315	390	470	630	780	1170
	3	18	55	92	147	220	275	365	460	550	730	920	1380
	3½	22	66	111	178	266	333	444	555	665	888	1110	1665
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	2½	10	30	50	79	118	150	200	250	300	400	495	750
	3	11	33	54	87	130	165	206	270	325	435	545	810
	3½	12	37	62	99	148	185	245	310	370	495	615	830
	4	15	44	73	117	176	220	295	365	440	585	735	1095
7	none	6	18	30	48	72	90	120	150	180	240	300	450
	3	7	22	37	59	88	110	145	185	220	295	365	555
	3½	8	24	40	64	96	120	160	200	240	320	400	600
	4	9	27	45	71	107	135	180	225	270	360	445	675
	4½	10	31	51	82	122	153	205	255	305	410	515	765
	5	12	37	61	98	147	185	245	305	370	490	615	915
8	none	4	14	23	36	55	69	92	115	135	185	230	345
	3½	5½	17	28	45	68	85	115	140	170	230	285	420
	4	6	18	30	49	73	90	122	150	180	240	305	450
	4½	6½	20	33	53	80	100	135	165	200	265	335	495
	5	7½	22	38	60	90	114	150	185	225	300	375	555

Reviewing the standard productions, it was available to use a cylinder with a Piston Diameter (3.5 Cm) and Rod Diameter (1.5 Cm).

The Stroke (S) = 0.3 m (Design Assumed Value).

Stroke Volume (V) = $A_{Piston} \times Stroke = 0.001 \times 0.3 = 0.0003\ m^3$

The load will be lifted during (5 seconds) - (Design Assumed Value).

So The required flow rate (Q) = Stroke Volume / Lift time = 0.0003 / 5 = 0.00006 m^3/s = 3.6 LPM

Hydraulic Power = P × Q = 500000 × 0.00006 = 30 watt = 0.04 HP

Taking Hydraulic efficiency through hoses and connections = 80%

So Pump Required power = 38 watt = 0.05 HP

(Taking pump overall Efficiency = 80%)

So Electric Motor Required Electrical Power = 47.5 watt = 0.063 HP.